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The metabolism of oil extraction: A bottom-up approach applied to the case of Ecuador

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ABSTRACT

The global energy system is highly dependent on fossil fuels, which covered approximately 90% of primary energy sources in 2016. As the quality and quantity of oil extracted changes, in response to changes in end uses and in response to biophysical limitations, it is important to understand the metabolism of oil extraction – i.e. the relation between the inputs used and the output extracted. We formalize a methodology to describe oil extraction based on the distinction between functional and structural elements, using the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) to generate a diagnostic of the performance of oil extraction and to build scenarios. The analysis allows generating modular benchmarks which are applicable to other countries. It is shown that oil extraction in Ecuador consumes, per cubic meter of crude oil extracted, over 100 kWh of electricity and 1.5 GJ of fuels, requiring 3 kW of power capacity and 2 h of human activity. A scenario is developed to check the effects on Ecuador's metabolic pattern of an increase in oil production over the next five years. The strength of the proposed methodology is highlighted, focusing on the adaptability of the method for dealing with policy issues.

1. Introduction

Despite efforts to reduce greenhouse gas (GHG) emissions and to shift towards a renewable energy system, oil remains an essential part of the global energy chain, with 3820 Mtoe consumed in 2015, out of a total final energy consumption of 9383 Mtoe (International Energy Agency, 2017). This is partly due to the fact that most renewable systems propose an alternative to electricity, rather than fuels. With sustainability issues tied to biofuels, particularly due to concerns over land use in relation to food security (Rathmann et al., 2010), as well as their low energetic output (Rajagopal et al., 2007), it is unlikely that conventional fuels will be phased out in the near future. Given the huge role that oil plays in societies, it is important to understand its metabolism – intended here as the interaction of internal factors determining the relation between the profile of inputs and outputs - particularly in relation to the internal consumption of energy carriers and other flows and funds (see Section 3.1 for a definition), such as water, chemicals, power capacity and human activity.

Most existing studies on the metabolism of the oil extraction sector account for one input of interest, as shown in Section 2. However, holistic assessments taking into consideration more than one fund or flow at a time, and at different levels, are lacking. Through the use of a Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM), one of the aims of this paper is to fill this methodological gap. We propose an alternative approach to formalize the grammar associated with the oil extraction process in Ecuador, following previous studies found in the literature for the oil and gas sector in Brazil (Aragão and Giampietro, 2016), the gas sector in Mexico (González-López and Giampietro, 2018) and for the electricity metabolism of Catalonia (Di Felice et al., this issue).

The aim of the paper is two-fold: on one hand, to develop methodological tools allowing us to describe the oil extraction process by accounting for various flows and funds across different levels; on the other, to apply the methodology to the case of Ecuador, both characterizing the factors determining the current metabolism and developing a scenario for future extraction and policy.

Section 2 provides background information as well as a review of existing literature. Section 3 outlines the rationale behind MuSIASEM and its proposed energy grammar, focusing on the distinction between functional and structural elements as applied to the oil extraction

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process; then, data sources and their reliability are discussed. Results and discussion are provided in Section 4, showing how the oil extraction grammar is built through a bottom-up approach. Finally, the paper illustrates a scenario of future oil extraction in Ecuador, showing how the modular bottom-up grammar can be applied to check constraints on future states. We end by summarizing the main findings, both with respect to the methodology and its possible broader applications in energy policy, and by highlighting areas for improvement and future research.

2. Background and literature review

Latin America is a net exporter of oil and gas, and public policies are pushing for an increase of extraction and refining capacity over the coming years, although regulations vary across countries (Hollanda et al., 2016). In Ecuador, as conventional oil stocks become depleted over time, government projections of reserves suggest that a shift from light and medium to heavy oil is gradually taking place (Secretaria de Hidrocarburos, 2016a). Oil extraction in Ecuador is minor (28 Mtoe in 2015) compared to other Latin American countries such as Mexico (131 Mtoe in 2015) or Brazil (133 Mtoe in 2015) (International Energy Agency, 2017). Nevertheless, extraction in Ecuador at the national level has been growing consistently over the past years, almost doubling between 2000 and 2014 (Hollanda et al., 2016). The amount of oil extracted is beyond the country's refining capacity, meaning that the country is a net exporter of crude oil, and net importer of fuel products. The two main energy policies in Ecuador over the past years have been, on one hand, the construction of new hydropower dams (MICSE, 2016) and, on the other, the development of refinement capacity, with the construction of a refinery *(Refinería del Pacífico* – Pacific Refinery) which will allow the processing of an additional 300,000 barrels of oil per day (MICSE, 2016), bridging the gap between oil extracted and fuels refined.

On the extraction side, since the reform on the hydrocarbon law of July 2010 (Asamblea Nacional, 2010), there has been a shift from participation contracts to service provision contracts. In 2012 a policy was established to "commercialize oil and its exported secondary products, preferably with state companies and public consumers" (author's translation, from (EP Petroecuador, 2012)). This allowed strengthening Ecuador's role in international markets, as it now has sale agreements on future oil lasting up to 2024. As a consequence, the country's economy would be strongly affected by a decrease in extraction over the coming years, especially if we take into account that, in 2015, oil exports accounted for 6662 Million dollars, or 36% of total exports (Ministerio de Comercio Exterior, 2016).

Overall, Ecuador's policy goals outlined in the national energy agenda of 2016–2040 point towards an extension of the hydrocarbon horizon, with a focus on crude oil and natural gas, in order to meet local consumption and increase exports. Within this context, it is important to understand how the current metabolism of oil extraction works, and to assess the effects of such policies on the country's future energy metabolism.

Zooming out of the case study at hand and looking at wider discourses of oil extraction, while the popularity and perceived urgency of the concept of peak oil varies across research groups, it is clear that there is a global shift towards the extraction of unconventional oil and oil shale, requiring higher technological and energetic investments (World Energy Council, 2016). Various assessments have been carried out focusing on the amount of energy needed to extract oil, mostly using energy return on energy investment (EROI) or life cycle assessments (LCA).

LCAs provide detailed overviews of the inputs and outputs of processes, but their role as input for policymaking has been questioned by various authors ((Ayres, 1995), chapter 4 of (Horne et al., 2009)). This is mostly due to three limitations: firstly, information is often reduced to a single parameter or indicator, which precludes the transparency of the calculation, providing a single output parameter rather than an overview of the process; secondly, choosing "the right" boundaries is problematic, leading to vastly different results being produced for the same process; thirdly, and most importantly for the current study, LCAs don't allow appropriate scaling across different levels of analysis. We will clarify what we mean by this through the steps of the proposed methodology.

Current assessments of oil extraction processes have mostly focused on either assessing oil reserves within a peak oil context (Owen et al., 2010), checking the environmental impacts of oil extraction (Bravo, 2007), or quantifying the energy returned on energy invested (EROI) (Court and Fizaine, 2017; Murphy and Hall, 2011). Extensions of EROI which use eMergy also exist (Chen et al., 2017), as well as other studies which analyze the EROI of particular technologies, such as biodiesel production (Poddar et al., 2017).

Most of the recent analyses on energy consumption in fossil fuel extraction focus on oil sands (Brandt et al., 2013b; Lazzaroni et al., 2016; Nimana et al., 2015). Brandt et al. (2013b), for instance, compute the energy return ratios for the period between 1970 and 2010, proposing an LCA-oriented methodology to calculate the energy return. An important difference between their methodology and the one presented here is that Brand et al.'s work does not split inputs into different energy carriers. We will argue that this distinction is of paramount importance to understand the behavior of energy systems. Other studies analyze particular cases of technologies, such as microalgae oil extraction (Peralta-Ruiz et al., 2013), including the energy consumption of the process by using exergy analysis.

In a different piece of work, Brandt et al. (2013a) present a bottom-up LCA-based and matrix-based approach for calculating systems-scale energy efficiency and net energy returns. To our knowledge, this is the closest exercise to the one presented here, as it allows working with different scales. Given the lack of distinction between funds and flows in Brand et al.'s work, the method presented here can be viewed as complementary to their approach, integrating it with additional information that can be of particular relevance to policy. Top-down, input-output methods have also been used to estimate the energy use of fossil fuels extraction, as in the case of shale gas extraction in China (Chang et al., 2014). Here, despite having information on the different inputs used in the process of shale gas extraction (energy carriers, water, sand, gravel, etc.), all inputs are converted into energy requirements. We argue that it is important to maintain a level of disaggregation in the description of inputs and outputs of the energy system.

Less attention is given in the literature to the use of water for the extraction of primary sources and their conversion to liquid fuels. Ali and Kumar (2017) provide an exception, by focusing on the water demand coefficients over the life cycle of fuels produced from crude oil. Their coefficients, although calculated for US wells, are of similar magnitude to the ones presented here.

Focusing back to the case of Ecuador, studies highlighting different dimensions of oil extraction have been carried out. FLACSO has produced a series of studies reviewing the current state of oil extraction in relation to sustainable development (Fontaine, 2003). From an environmental justice perspective, a number of studies have assessed the social and environmental impacts of oil extraction on local populations (see, for example, (Vallejo et al., 2015) and (Rodríguez, 1998)). The environmental impacts of oil extraction on aquifers and water consumption have not been assessed specifically for Ecuador, but studies on the topic exist, for example in relation to deep sea drilling (Cordes et al., 2016) and shale gas extraction (Vidic et al., 2013).

In order to contribute to the debate on the metabolism of oil extraction, this study presents the application of a new methodology of accounting for the different funds and flows employed, as described in the next section.